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Evaluation of Power Flow Control for an All-Electric Warship Power System with Pulsed Load Applications

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Abstract

Future U.S. Navy ships will require power systems that meet more stringent agility, efficiency, scalability, controllability, and resiliency requirements. To satisfy these requirements, alternative methods for controlling and analyzing networked microgrids are investigated. Investigating these systems will provide insight into tradeoffs that can be made during the design phase. This paper considers the problem of electric ship power disturbances in response to pulsed loads, in particular, to electromagnetic launch systems (EMALS). A trade-off between information flow and power flow is given to potentially enable a reduction in energy storage hardware requirements.

Electric Ship Reference Model

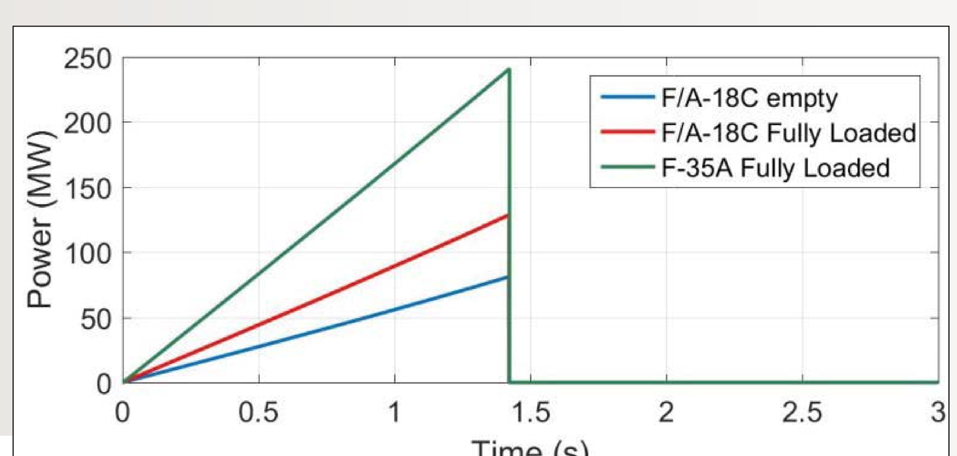
3-Zone Power System

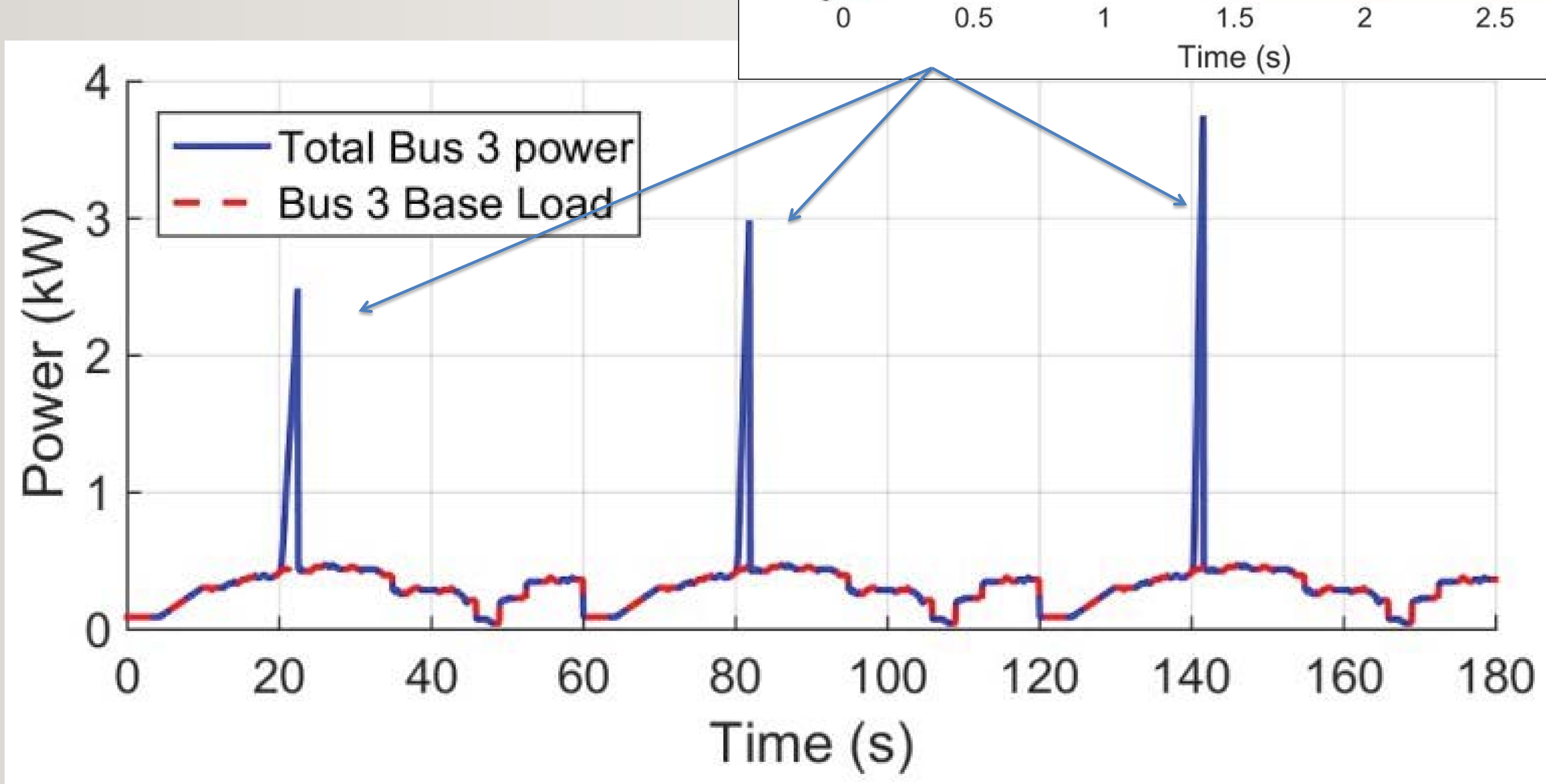
A notional electric ship was developed based on typical power levels and architectures identified in open literature; it uses a high-voltage DC bus, relies heavily on power electronic converters to provide flexible power flow control, and includes a network to enable communication.

Pulsed Load: Electromagnetic Launch System (EMALS)

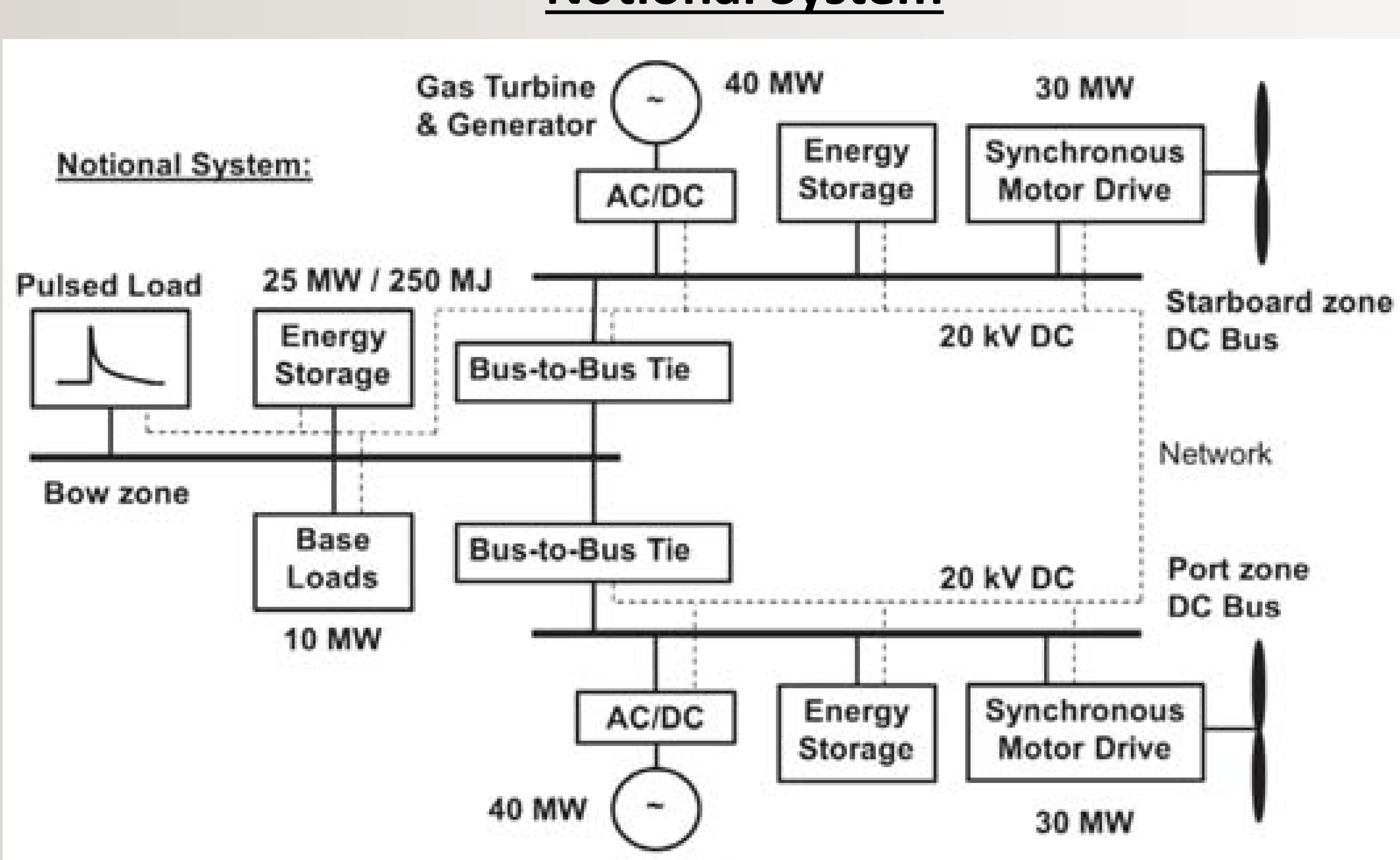
The EMALS is a major component of the electric ship that will replace more conventional steam powered launch systems. The system must be capable of accelerating an aircraft to a launch speed of up to 103 m/s over the course of a ship's runway, approximately 73 m. The expected power draw required of an EMALS system, along with the base load is shown.

EMALS Power Pulse:





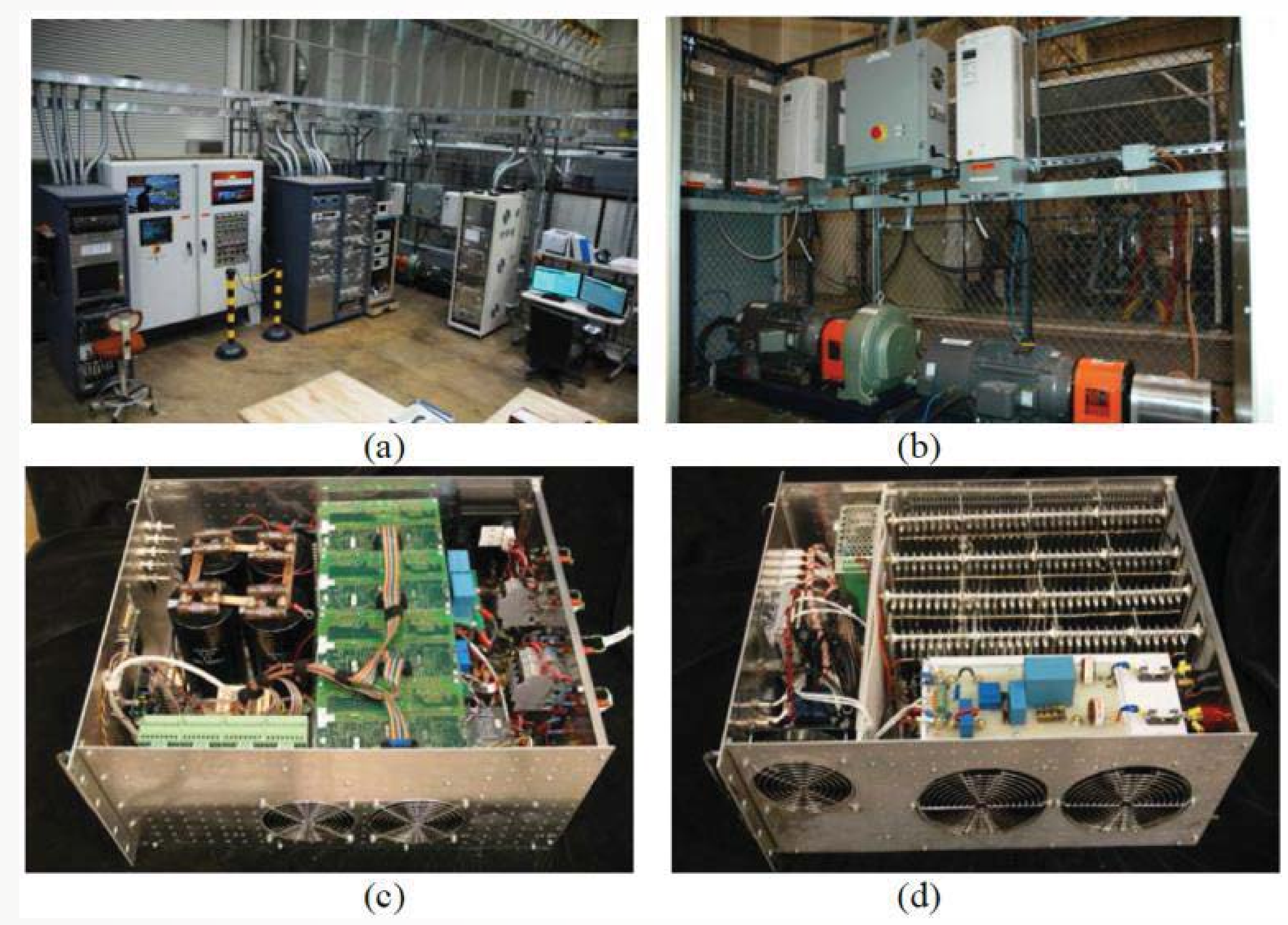
Notional System

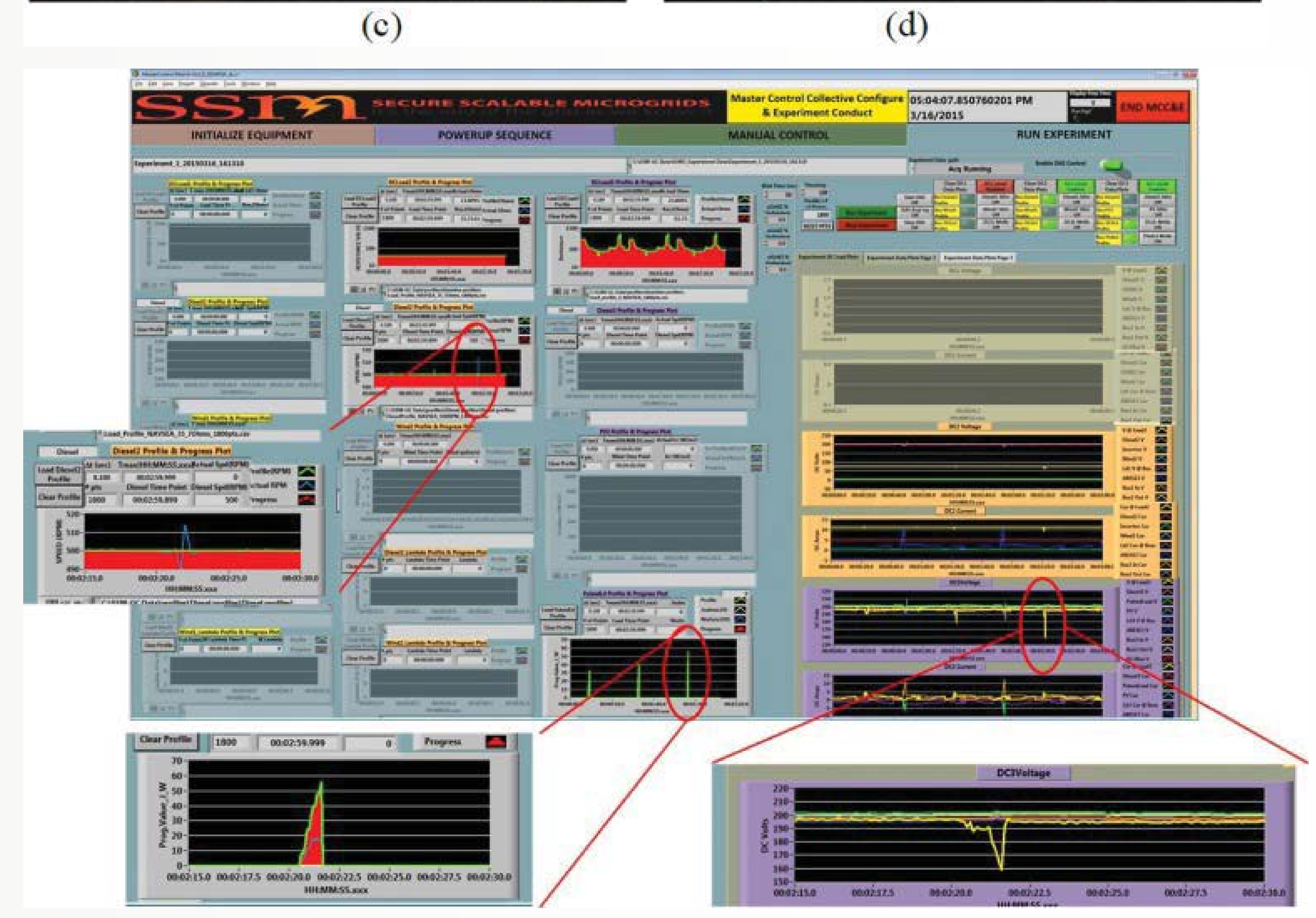


Microgrid Testbed Description

Secure Scalable MicroGrid Test Bed (SSMTB)

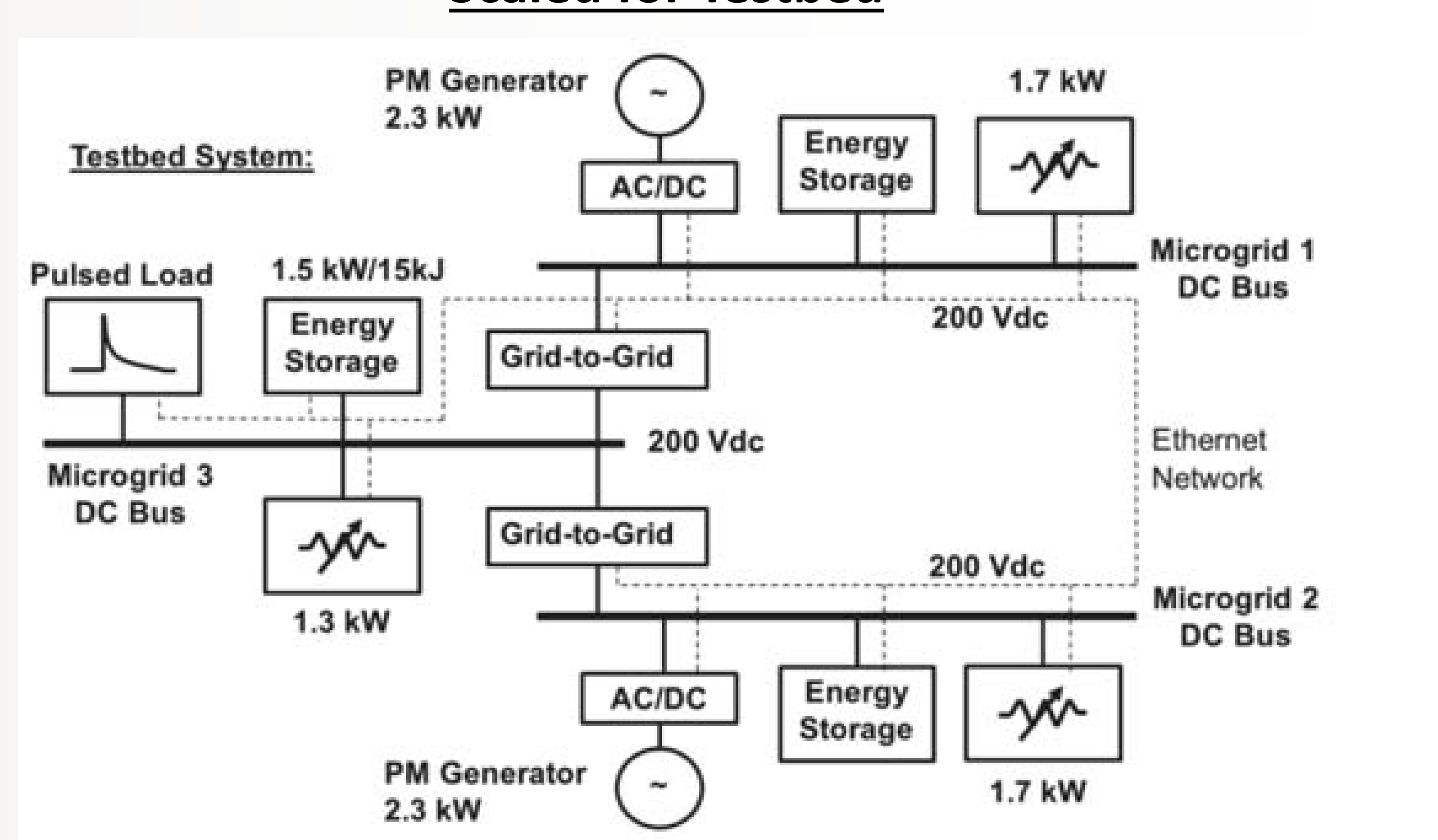
The Secure Scalable MicroGrid Test Bed (SSMTB) was designed to conduct experiments on networked microgrids that share information flow and power flow. The testbed includes three microgrid systems, a reconfigurable bus cabinet for interconnecting the components, and computers used for control, data acquisition, and situational awareness. The microgrid systems are comprised of magnet generators, energy storage emulators, mechanical source emulators based on commercial motor drives, several power electronic converters, and programmable resistive loads. A master control console scripts experiments with designated source and load profiles.





The notional system was scaled down and emulated using components in the SSMTB, thus providing a laboratory scale model of a 3-zone electric ship networked power system.

Scaled for Testbed



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Power Flow Control Strategy

The model can be defined in matrix form as:

$$M\dot{x} = Rx + v + u$$

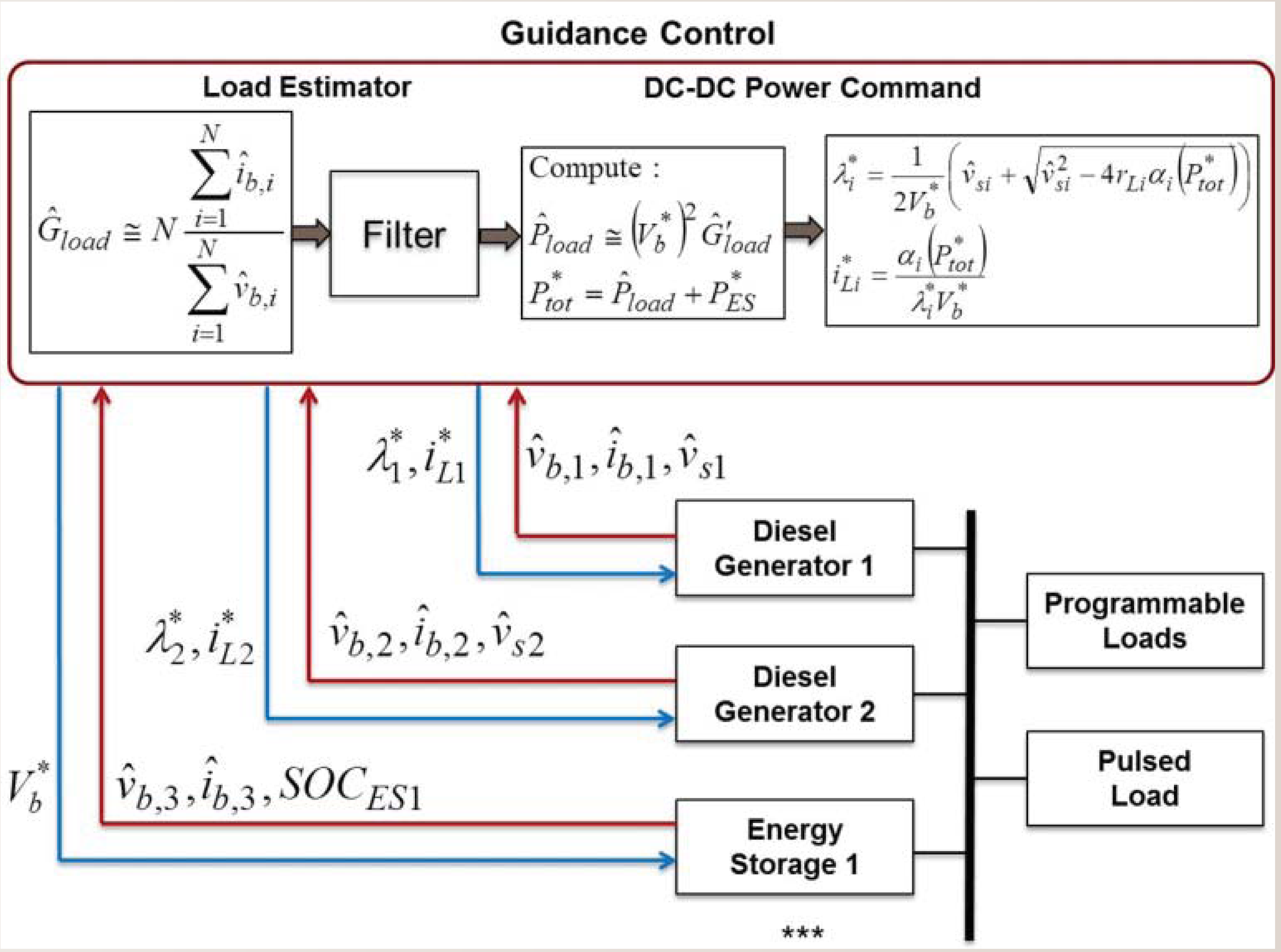
where the M matrix consists of the passive energy storage elements (inductance, capacitance) of the circuit and the R matrix consists of the resistive elements of the circuit, and x is the system state. The v-vector consists of the general source inputs to the network and the u-vector contains the controller inputs. The R matrix is decomposed further as the sum of a diagonal and skew-symmetric matrix components.

The nonlinear control design architecture based on *Hamiltonian Surface Shaping and Power Flow Control* (HSSPFC) uses a power flow approach that balances generation and dissipation subject to power storage (kinetic and potential energies) which define the Hamiltonian for the system or static stability. The dynamic stability condition is given by the rate of the Hamiltonian:

$$\dot{H} = -\Delta x^T \left[K_P - \bar{R} \right] \Delta x < 0$$

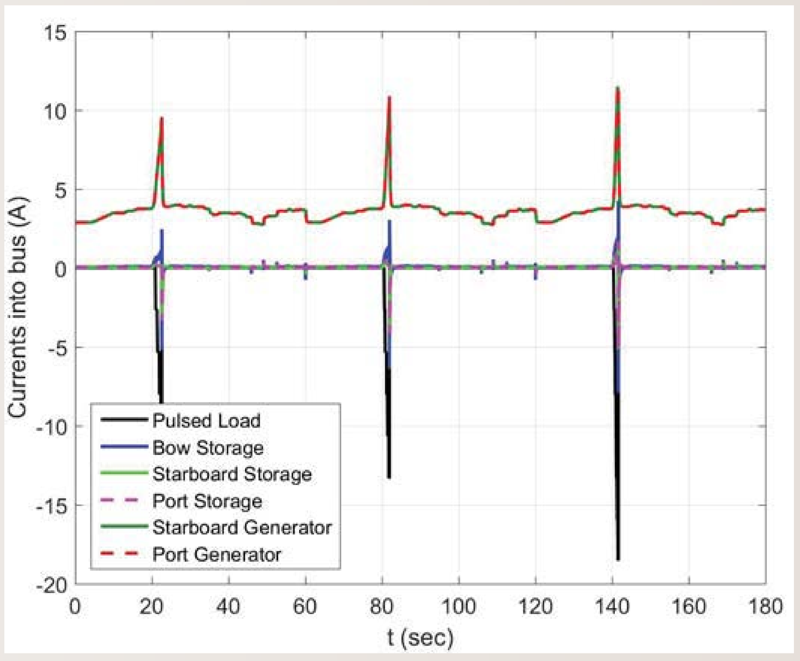
Guidance Control

The guidance controller provides regular updates to the power converters in the system. The generators and energy storage communicate current and voltage measurements. The guidance controller sends voltage references to the energy storage units which then regulate bus voltage. The guidance controller also sends power commands to the converters that connect generators to the bus. Power requirements are computed using a real-time load estimator and predesignated voltage set points.

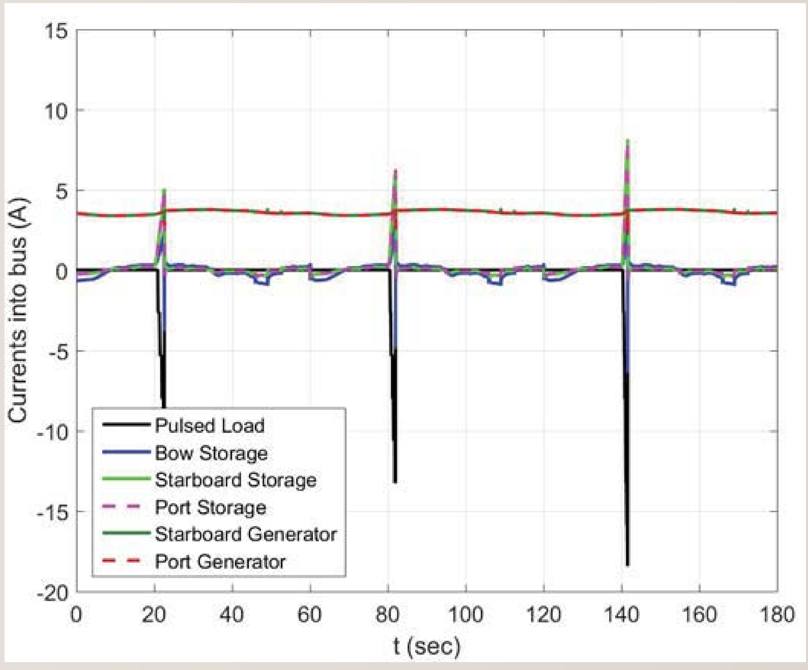


Simulation Results

Simulink simulation was performed on the scaled system; five 180 second simulation experiments were done with filter time constants of (1) 0.1356, (2) 0.5299, (3) 2.005, (4) 7.512, and (5) 28.56 seconds. Each had three simulated EMALS launches of different potential plane configurations and a varying base load.



Generator Response for time constant of 0.1356 seconds



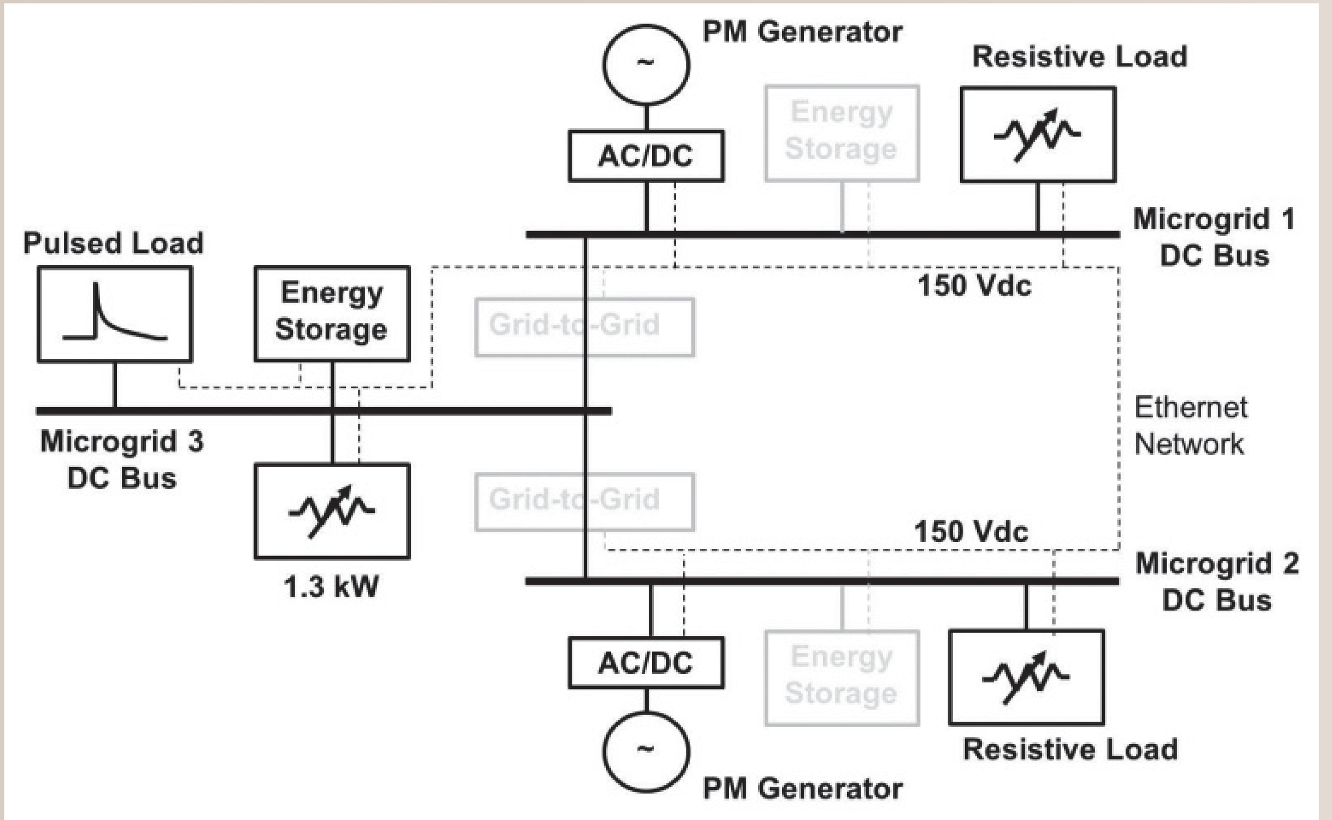
Generator Response for time constant of 28.56 seconds

Experimental Results

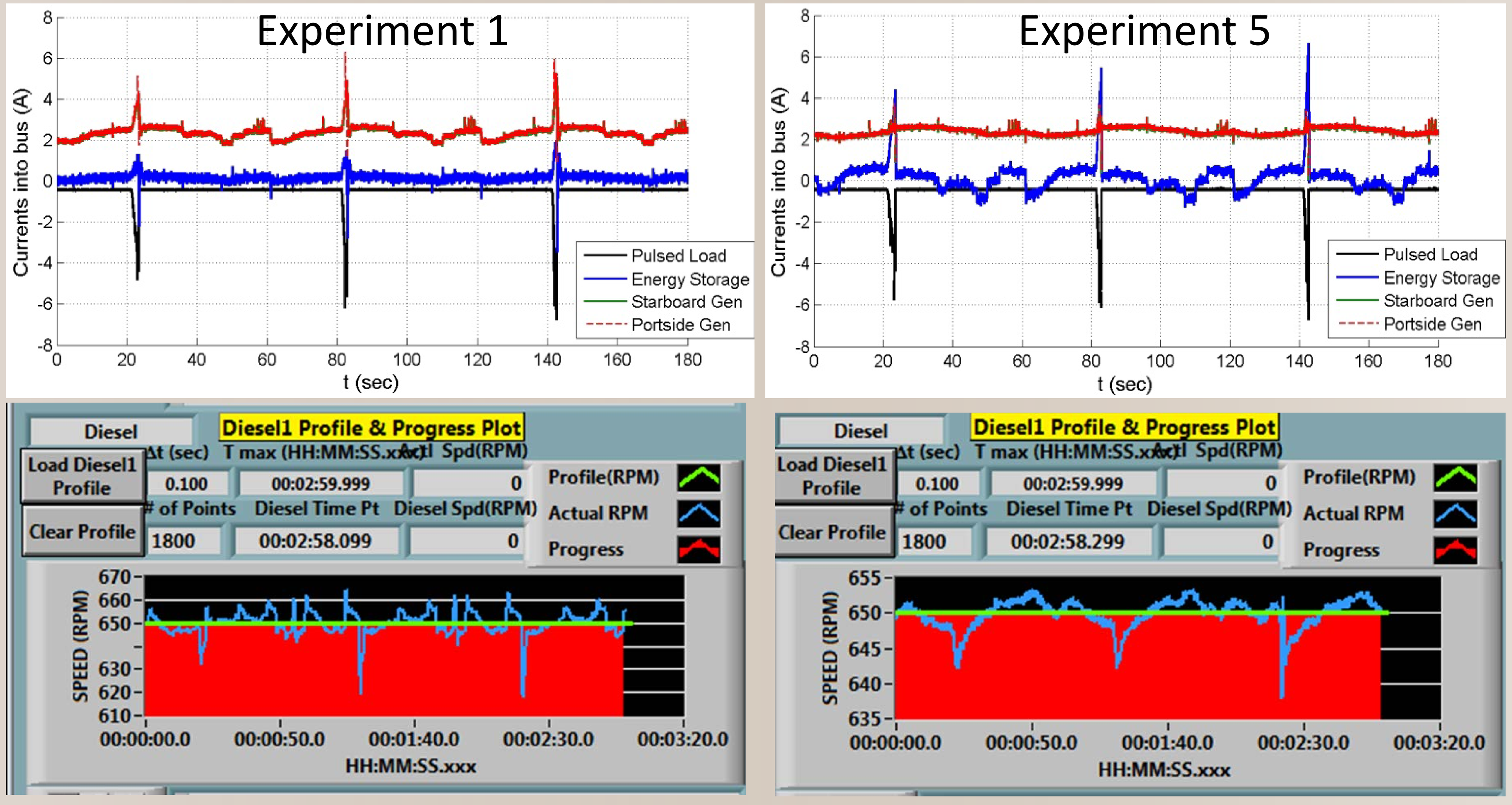
The hierarchical control was evaluated in a series of five hardware experiments on selected components. Each experiment ran for 180 seconds with both generators engaged, the propulsion load was represented as a constant resistance, the variable load on Microgrid 3 (Bow zone) was varied to represent three simulated EMALS launches and a varying base load.

Hardware Experiment Setup

- 3 zones
- 2 generators
- 1 Energy storage unit
- 2 propulsion loads
- 1 variable load
- 1 pulsed load



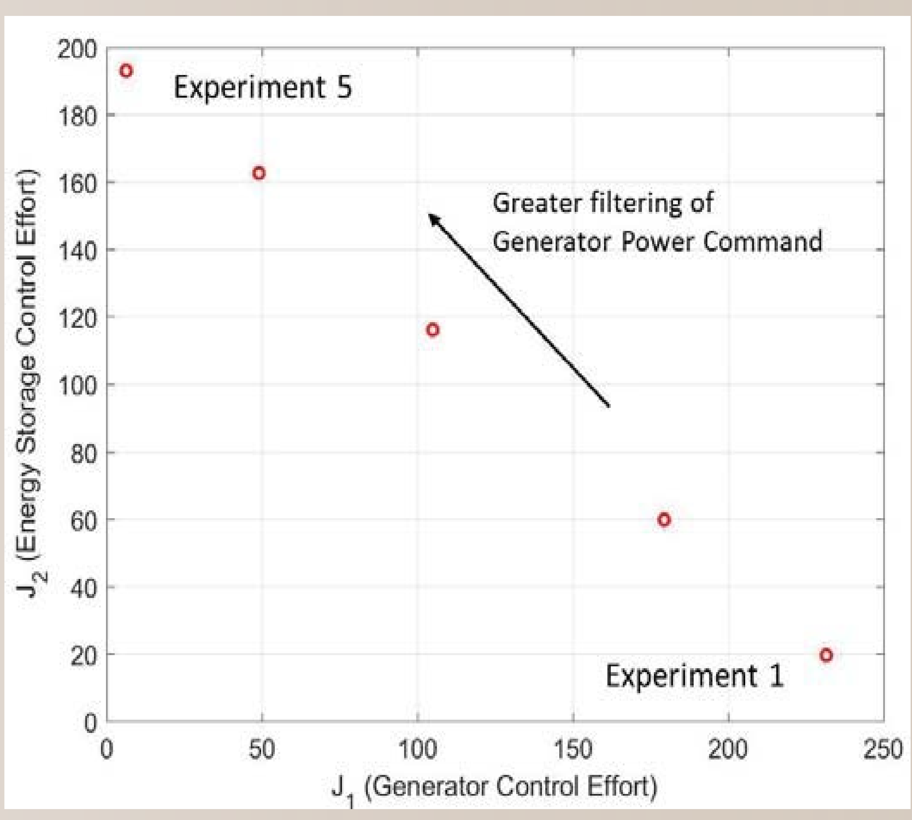
In experiment 1, it is noted that the energy storage current is minimal. The majority of the baseload power and pulsed load are tracked by the generators. Experiment 5 shows the generator currents varying slowly, with the baseload and pulsed power demands tracked by the energy storage.



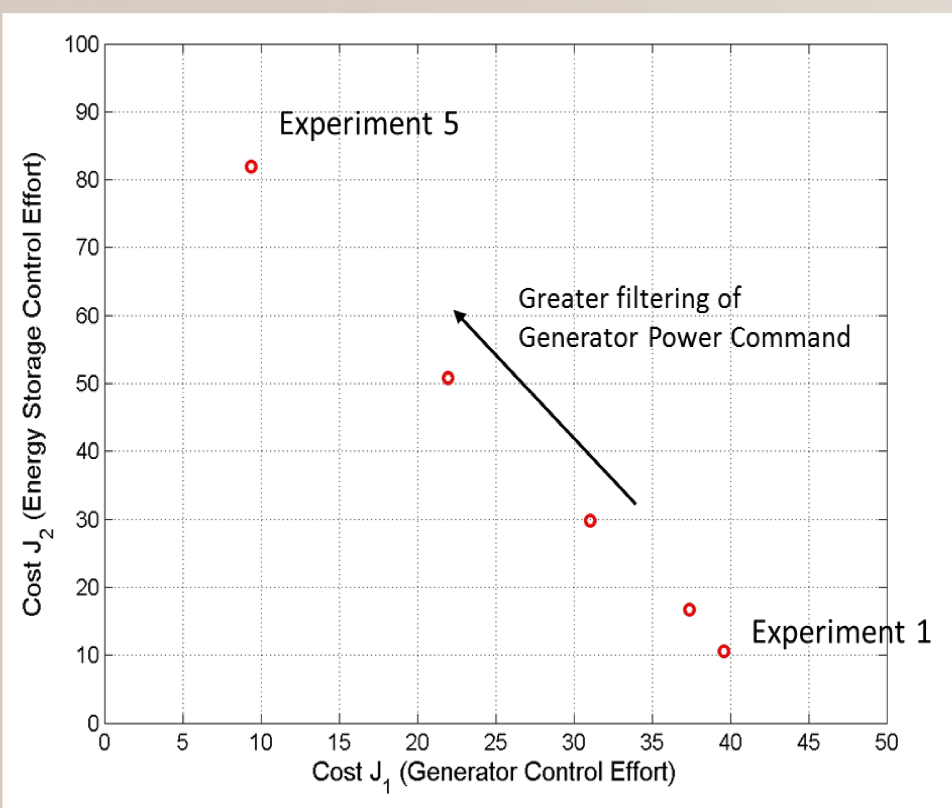
Design Trade-off

This guidance control function is capable of designating where the pulsed power is supplied (energy storage units or generator inertia) through manipulation of a filter time constant. This was demonstrated in simulation and experimentation.

Simulated Trade Space



Experimental Trade Space



ACKNOWLEDGEMENTS

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NNSA National Nuclear Security Administration

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